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ISO Observations of Star-forming Galaxies

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Abstract. The Infrared Space Observatory *(ISO)* is used to carry out mid-IR (7 and 15 µm) and far-IR (90 µm) observations of a sample of star-forming sub-mJy radio sources. By selecting the sample at radio wavelengths, one avoids biases due to dust obscuration. It is found that the mid-IR luminosities, covering the PAH features, measure the star formation rate for galaxies with $P_{1.4GHz} < 10^{23}$ W Hz^{-1}. This is further confirmed using the Hα luminosities. The far-IR emission is also found to trace the SFR over the whole range of radio and Hα luminosities. The implication of the mid-IR measurements in estimating the SFRs from the future infrared space missions (SIRTF and ASTRO-F) is discussed.

1 Introduction

There now exist several measurements of the star formation rate (SFR) at different redshifts, based on UV [1,2,3] and Balmer-line [4,5,6,7] studies, with the latter yielding estimates a factor of 2–3 times higher than the former, presumably because of differential dust extinction. These disagreements impede progress in understanding the evolution with redshift of the rates of star-formation and heavy element production [8]. The problem becomes more serious at high redshifts due to changes in dust content in galaxies with look-back time. In particular, optically selected samples are likely to be biased against actively star-forming and dusty galaxies, leading to an underestimation of the SFR from these samples. Indeed, it has been shown that a large fraction of the bolometric luminosity emerges at far–IR wavelengths, with recent observations with the Infrared Space Observatory (ISO) showing that the contribution to the cosmic infrared background is dominated by infrared luminous galaxies. This confirms that most of the star formation, specially at high redshifts, is hidden in dusty environments. Also, it is shown that different star-formation diagnostics give different SFRs even for the same galaxy. Therefore, to accurately trace the SFR, one needs to use as many *independent* star-formation diagnostics as possible.

In this study, the sensitivity of the mid-IR fluxes (7-15 µm), covering the PAH features, to the star-formation activity in galaxies will be studied, using an unbiased sample of star-forming galaxies. The potential of this technique in measuring the SFRs at $z \sim 2$ is then discussed.

2 Sample Selection

The sample for this study consists of sub-mJy radio sources, selected at radio (1.4 GHz) wavelengths [9] and hence, is free from dust-induced selection biases. A total of 400 of these galaxies are then spectroscopically observed with their redshifts measured and spectral features (Hα, MgII, etc) identified [10]. A sample of 65 radio sources were then observed with ISOCAM (7 and 15 µm) and ISOPHOT (90 µm)- (Afonso et al 2001, *in preparation*). The objects adopted for *ISO* observations are chosen to be sub-mJy radio sources, showing evidence for star-formation activity in their spectra and sufficiently bright at mid- to far- IR wavelengths (as predicted from their SEDs) to allow detection at these wavelengths. The number of radio sources in the *ISO* survey region, together with the number of galaxies with detections at the three *ISO* wavelengths are listed in Table 1. The ISOCAM pointed survey also resulted in the serendipitous detection of 26 sources for which no radio counterpart was found. These objects will not be discussed here. Details about the *ISO* observations and data reduction will be presented in a future paper (Afonso et al 2001, *in preparation*).

Table 1. Number of sources in the the areas covered by both the *ISO* and radio surveys. N_s and N_d denote, respectively, the number of radio sources over the area covered by the *ISO* (65 pointings for ISOCAM, and 44 for ISOPHOT) and the number of *ISO* detected sources.

Band	N_s	N_d
7 µm	146	16
15 µm	146	15
90 µm	44	9

3 Results

The intrinsic luminosities at the *ISO* and radio wavelengths are estimated assuming $H_0 = 65$ km/sec/Mpc. The K-corrections are applied, assuming a flat spectrum at 7 and 15 µm wavelengths. For the 90 μm and 1.4 GHz fluxes, a power-law SED of the form $f_\nu \propto \nu^n$ is assumed with spectral indices of respectively $n = -2$ and -0.7.

The ratio of the *ISO* (7, 15, 90 µm) to radio power as a function of the radio power for galaxies in the present sample is shown in Fig. 1. Both the detections and upper limits are included in this diagram. Figure 1 is significant in that, the lack of a trend here indicates that the radio, compared to mid-IR and far-IR luminosities measure the *same* quantity (ie. star-formation)

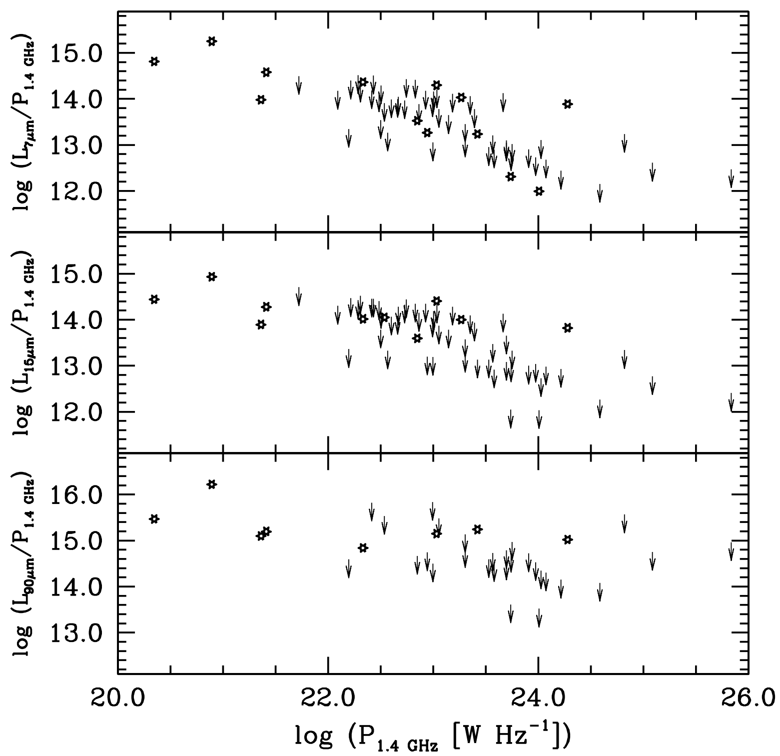

Fig. 1. Ratio of the *ISO* luminosities to the radio power as a function of the radio (1.4 GHz) power. $L_{7\,\mu m}$, $L_{15\,\mu m}$ and $L_{90\,\mu m}$ are defined as νP_ν at the respective rest-frame wavelength and are given in units of $L_\odot$.

whereas, the presence of a trend implies that they are sensitive to *different* physical processes.

The $L_{7\,\mu m}/P_{1.4\,\mathrm{GHz}}-P_{1.4\,\mathrm{GHz}}$ and $L_{15\,\mu m}/P_{1.4\,\mathrm{GHz}}-P_{1.4\,\mathrm{GHz}}$ relations both show a slight trend for $\log(P_{1.4\,\mathrm{GHz}}) < 10^{23}$ W/Hz, followed by a steep slope at $\log(P_{1.4\,\mathrm{GHz}}) > 10^{23}$ W/Hz. The value of 10^{23} W/Hz corresponds to the characteristic radio power of the sub-mJy sources where also a change of slope is found in the 1.4 GHz luminosity function of star-forming galaxies [13]. Assuming that the radio emission from galaxies is a measure of the synchrotron radiation due to relativistic electrons, produced by supernovae remnants, and hence their SFR [11,12], one concludes that for $P_{1.4\,\mathrm{GHz}} < 10^{23}$ W/Hz, the mid-IR (7 and 15 μm) luminosity is sensitive to the star-formation activity. However, for objects with $P_{1.4\,\mathrm{GHz}} > 10^{23}$ W/Hz, the PAH molecules are destroyed due to the strength of the photon field, resulting a decrease in the mid-IR flux from galaxies. At the far-IR 90 μm wavelength, there is no significant trend on the $L_{90\,\mu m}/P_{1.4\,\mathrm{GHz}} - P_{1.4\,\mathrm{GHz}}$ diagram, confirming that both

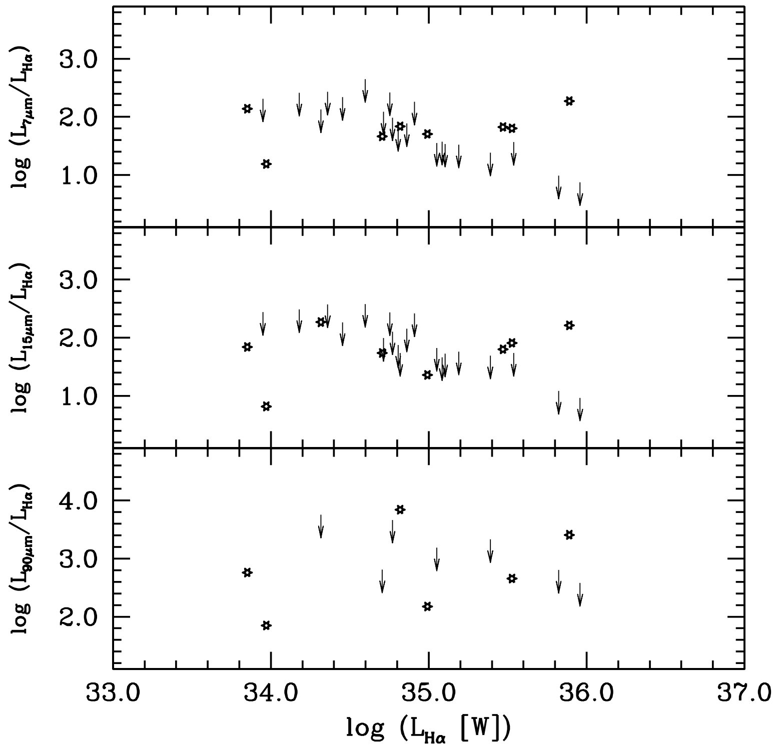

Fig. 2. Ratio of the *ISO* mid and far-IR luminosities to Hα luminosity as a function of Hα luminosity.

the far-IR and radio luminosities measure the same quantity (ie. SFR). These results are obtained using both the detections and upper limits. Using only the detections, the trend in the relation disappears at 15 μm while remains the same for 7 μm.

The above results are confirmed using Hα line luminosity (Figure 2) which is a more direct measure of the star-formation in galaxies. While there is a small trend on the $L_{7\mu m}/L_{H\alpha} - L_{H\alpha}$ relation for $L_{H\alpha} > 10^{34.8}$ W, the trend almost disappears for $L_{15\mu m}/L_{H\alpha} - L_{H\alpha}$ and is entirely absent on the $L_{90\mu m}/L_{H\alpha} - L_{H\alpha}$ relation. This implies an increase in the sensitivity to the star-formation from 7 to 15 and 90 μm wavelengths, in agreement with the results from Figure 1.

The results in this study can be used to establish new star-formation diagnostics, based on 7 and 15 μm luminosities, and to calibrate them. This has significant implications for future mid-IR surveys with the SIRTF and ASTRO-F. For example, a 24 μm deep survey, planned with the SIRTF, can detect the rest-frame 7 and 15 μm emissions at $z = 2.4$ and $z = 0.6$

respectively, allowing measurement of the SFRs between these redshifts. By selecting a sample at radio wavelengths, with follow-up mid-IR observations, one could then avoid dust-induced selection biases in estimating the SFR.

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